

Security-Reliability Trade-off Analysis of Multi-Relay Aided Decode-and-Forward Cooperation Systems

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Abstract—We consider a cooperative wireless network comprised of a source, a destination and multiple relays operating in the presence of an eavesdropper, which attempts to tap the source-destination transmission. We propose multi-relay selection scheme for protecting the source against eavesdropping. More specifically, multi-relay selection allows multiple relays to simultaneously forward the source's transmission to the destination, differing from the conventional single-relay selection where only the best relay is chosen to assist the transmission from the source to destination. For the purpose of comparison, we consider the classic direct transmission and single-relay selection as benchmark schemes. We derive closed-form expressions of the intercept probability and outage probability for the direct transmission as well as for the single-relay and multi-relay selection schemes over Rayleigh fading channels. It is demonstrated that as the outage requirement is relaxed, the intercept performance of the three schemes improves and vice versa, implying that there is a *security versus reliability trade-off* (SRT). We also show that both the single-relay and multi-relay selection schemes outperform the direct transmission in terms of SRT, demonstrating the advantage of the relay selection schemes for protecting the source's transmission against the eavesdropping attacks. Finally, upon increasing the number of relays, the SRTs of both the single-relay and multi-relay selection schemes improve significantly and as expected, multi-relay selection outperforms single-relay selection.

Index Terms—Security-reliability trade-off, relay selection, intercept probability, outage probability, eavesdropping attack.

I. INTRODUCTION

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Manuscript received January 22, 2015; revised May 3, 2015; accepted July 3, 2015. This work was partially supported by the National Natural Science Foundation of China (Grant Nos. 61302104 and 61401223), the Scientific Research Foundation of Nanjing University of Posts and Telecommunications (Grant Nos. NY213014 and NY214001), and the Natural Science Foundation of Jiangsu Province (Grant No. BK20140887). The review of this paper was coordinated by Dr. Chengwen Xing. (*Corresponding author: Yulong Zou.*)

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WIRELESS security has attracted increasing research attention in recent years [1], [2]. Due to the broadcast nature of wireless medium, legitimate transmissions may readily be tapped by unauthorized users, leaving them vulnerable to eavesdropping attacks. Traditionally, cryptographic techniques have been adopted for protecting the confidentiality of legitimate transmissions against eavesdropping. Although classic cryptographic approaches relying on secret keys indeed do enhance the transmission security, this imposes both an extra computational overhead and additional system complexity, for example when distributing and managing the secret keys. Additionally, the classic cryptographic techniques are not perfectly secure, since they can still be decrypted by an eavesdropper with a sufficiently high computing power through exhaustive key search.

Alternatively, physical-layer security [3], [4] is emerging as a promising paradigm against eavesdropping attacks, which relies on exploiting the physical characteristics of wireless channels. In [5], Leung-Yan-Cheong and Hellman proved that as long as the wiretap channel (spanning from the source to the eavesdropper) is a degraded version of the main channel (spanning from the source to the destination), the source-destination transmission can be perfectly reliable and secure. They also introduced the notion of secrecy capacity, which is the maximal rate achieved by the destination under the condition that the mutual information between the source and eavesdropper remains zero. It was shown in [5] that the secrecy capacity is the difference between the capacity of the main channel and that of the wiretap channel. In [6] and [7], the secrecy capacity of wireless fading channels was further developed from an information-theoretic perspective. Moreover, the use of multi-input multi-output (MIMO) [8], cooperative relaying [9], [10] and beamforming techniques [11] was studied for the sake of combating the fading effects and for improving the wireless secrecy capacity.

Recently, the transmit antenna selection has been studied in [12]–[15] for enhancing the physical-layer security of wireless communications. In [12], the authors examined the secrecy outage performance of the transmit antenna selection in a multi-input single-output (MISO) system in the face of a multi-antenna eavesdropper. It was shown in [12] that the secrecy outage probability of the MISO system relying on transmit antenna selection is significantly reduced. In [13], the transmit antenna selection was further extended to a MIMO system and a closed-form secrecy outage expression of the

transmit antenna selection aided MIMO system was derived in fading environments. After that, the authors of [14] studied the effect of outdated channel state information (CSI) on the secrecy performance of transmit antenna selection and showed that the secrecy outage probability expectedly degrades in the presence of the outdated CSI. Additionally, the secrecy diversity of the transmit antenna selection assisted MIMO communications was examined in [15], where an asymptotic secrecy outage probability is characterized in high main-to-eavesdropper ratios (MERs).

In this paper, we explore the physical-layer security of a cooperative relay network in the presence of an eavesdropper, with an emphasis on the security-reliability trade-off (SRT) of cooperative relay communications based on the decode-and-forward (DF) protocol without considering the amplify-and-forward (AF). As discussed in [16], in the AF protocol, the relay just simply re-transmits a scaled version of its received signal from the source to the destination. This, however, has the relay noise propagation issue, since the noise received at the relay will be propagated to the destination. By contrast, the DF protocol allows the relay to decode its received signal. If the relay succeeds in decoding e.g. through the use of cyclic redundancy code (CRC), it then re-transmits its decoded signal to the destination, which is called an adaptive DF [16]. It was shown in [16] that the adaptive DF achieves a better performance than the AF in terms of the frame error rate (FER). Motivated by this fact, the DF protocol is adopted in this paper. Although only the DF is considered, similar SRT results can be obtained for the AF protocol.

It is pointed out that the notion of SRT was first introduced in [17] and [18], where the wireless security and reliability are characterized by the intercept probability (IP) and outage probability (OP), respectively. In this paper, we investigate the single-relay and multi-relay selection for the sake of improving the physical-layer security of general wireless networks, instead of cognitive radio networks as studied in [18]. We derive closed-form expressions of the IP and OP for both the single-relay and multi-relay selection schemes and show that the multi-relay selection consistently outperforms the single-relay selection in terms of its SRT.

The remainder of this paper is organized as follows. In Section II, we present the single-relay and multi-relay selection schemes for enhancing the attainable wireless physical-layer security and compare them against the classic direct transmission. Next, in Section III, we carry out the SRT analysis of these three schemes over Rayleigh fading channels, followed by Section IV, where numerical SRT results are presented. Finally, we provide our concluding remarks in Section V.

II. SINGLE AND MULTIPLE RELAY SELECTION AGAINST EAVESDROPPING

A. Direct Transmission

Let us first consider the direct transmission as a benchmark invoked for comparison purposes. Fig. 1 depicts a wireless system, where a source (S) transmits its scalar signal x_s ($E[|x_s|^2] = 1$) to a destination (D) at a particular time instant, while an eavesdropper (E) attempts to tap the source's

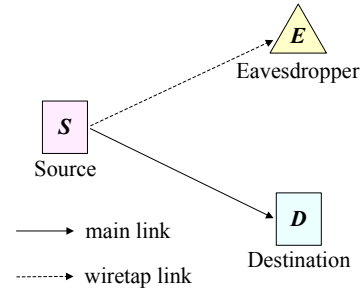


Fig. 1. A wireless network comprised of a source (S) and a destination (D) in the presence of an eavesdropper (E).

transmission. In line with the physical-layer security literature [2]-[9], E is assumed to know the encoding and modulation schemes as well as the encryption algorithm and secret key of the S-D transmission, except for the source signal x_s . When S transmits x_s at a power of P , we can express the received signal at D as

$$y_d = h_{sd}\sqrt{P}x_s + n_d, \quad (1)$$

where h_{sd} is the fading coefficient of the S-D channel and n_d is the AWGN at D. Meanwhile, due to the broadcast nature of wireless transmission, the transmission of S can be overheard by E and the corresponding received signal is written as

$$y_e = h_{se}\sqrt{P}x_s + n_e, \quad (2)$$

where h_{se} is the fading coefficient of the S-E channel and n_e represents the AWGN at E. From (1), we obtain the channel capacity between S and D as

$$C_{sd} = \log_2(1 + |h_{sd}|^2\gamma), \quad (3)$$

where $\gamma = P/N_0$. Similarly, the channel capacity between S and E is obtained from (2) as

$$C_{se} = \log_2(1 + |h_{se}|^2\gamma). \quad (4)$$

Throughout this paper, the Rayleigh fading model is considered for characterizing a transmission link between any two nodes of Fig. 1. Although only the Rayleigh fading is considered in this paper, similar SRT analysis and results can be obtained for other wireless fading models e.g. Nakagami fading and Rice fading. Moreover, the complex additive white Gaussian noise (AWGN) encountered at the receiver has a zero mean and a variance of N_0 .

B. Single-Relay Selection

In this subsection, we consider the cooperative wireless network illustrated in Fig. 2, where both D and E are out of the coverage area of S, and N relays are used for assisting the transmission of S. We invoke the decode-and-forward (DF) protocol for the relays in forwarding the transmission of S to D. More specifically, S first broadcasts x_s to the N relays, which attempt to decode x_s . For notational convenience, let \mathcal{D} denote the set of relays that successfully decode x_s , which is termed as the *decoding set*. Given N relays, there are 2^N possible subsets \mathcal{D} , thus the sample space of \mathcal{D} is given by

$$\Omega = \{\emptyset, \mathcal{D}_1, \mathcal{D}_2, \dots, \mathcal{D}_n, \dots, \mathcal{D}_{2^N-1}\}, \quad (5)$$

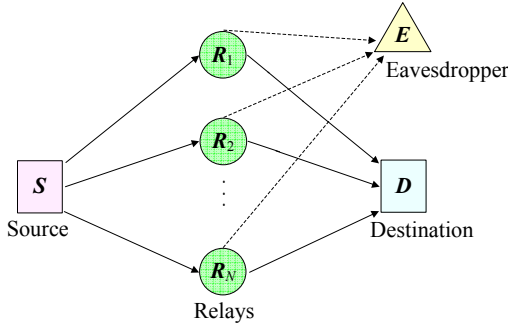


Fig. 2. A cooperative wireless network consisting of one source (S), one destination (D) and N relays (R_i) in the presence of an eavesdropper (E).

where \emptyset denotes an empty set and \mathcal{D}_n denotes the n -th non-empty subset of the N relays. If the set \mathcal{D} is empty (i.e., no relay succeeds in decoding x_s), all relays remain silent and thus both D and E are unable to decode x_s in this case. If the set \mathcal{D} is non-empty, a specific relay is chosen from \mathcal{D} for forwarding its decoded signal x_s to D. Therefore, considering that S broadcasts x_s to N relays at a power of P , the received signal at a specific relay R_i is expressed as

$$y_i = h_{si}\sqrt{P}x_s + n_i, \quad (6)$$

where h_{si} is the fading coefficient of the channel spanning from S to R_i and n_i is the AWGN at R_i . From (6), we obtain the channel capacity between S and R_i as

$$C_{si} = \frac{1}{2} \log_2(1 + |h_{si}|^2\gamma), \quad (7)$$

where the factor $\frac{1}{2}$ in the front of $\log(\cdot)$ arises from the fact that two time slots are required to complete the transmission of S to D via R_i . It is readily inferred from Shannon's coding theorem that if the channel capacity is lower than the data rate, the receiver is unable to recover the source signal. Otherwise, the receiver becomes capable of successfully decoding. Hence, by using (7), the event $\mathcal{D} = \emptyset$ is described as

$$C_{si} < R, \quad i = 1, 2, \dots, N, \quad (8)$$

where R is the data rate. Meanwhile, the event $\mathcal{D} = \mathcal{D}_n$ can be described as

$$\begin{aligned} C_{si} &> R, \quad i \in \mathcal{D}_n \\ C_{sj} &< R, \quad j \in \bar{\mathcal{D}}_n, \end{aligned} \quad (9)$$

where $\bar{\mathcal{D}}_n$ is the complementary set of \mathcal{D}_n . Without any loss of generality, we consider R_i as the "best" relay, which transmits its decoded signal x_s at a power of P . Hence, the received signal at D is written as

$$y_d = h_{id}\sqrt{P}x_s + n_d, \quad (10)$$

where h_{id} is the fading coefficient of the channel spanning from R_i to D. From (10), the capacity of the channel between R_i and D is given by

$$C_{id} = \frac{1}{2} \log_2(1 + |h_{id}|^2\gamma), \quad (11)$$

where $i \in \mathcal{D}_n$. Typically, the relay having the highest capacity between R_i and D is viewed as the "best" one. Thus, from

(11), we obtain the selection criterion of finding the best relay as

$$\text{Best Relay} = \arg \max_{i \in \mathcal{D}_n} C_{id} = \arg \max_{i \in \mathcal{D}_n} |h_{id}|^2, \quad (12)$$

which shows that only the knowledge of the CSI $|h_{id}|^2$ is assumed in performing the relay selection, i.e. it is carried out without requiring the eavesdropper's CSI knowledge. Notice that in practical wireless systems, the CSI of the main channel (i.e., $|h_{id}|^2$) can be obtained by using some channel estimation methods [19]. Combining (11) and (12), we obtain the capacity of the channel between the "best" relay and D as

$$C_{bd} = \frac{1}{2} \max_{i \in \mathcal{D}_n} \log_2(1 + |h_{id}|^2\gamma), \quad (13)$$

where the subscript 'b' represents the best relay. Meanwhile, given that the selected relay transmits x_s at a power of P , the signal received at E is written as

$$y_e = h_{be}\sqrt{P}x_s + n_e, \quad (14)$$

where h_{be} is the fading coefficient of the channel spanning from the "best" relay to E. From (14), we express the capacity of the channel spanning from the "best" relay to E as

$$C_{be} = \frac{1}{2} \log_2(1 + |h_{be}|^2\gamma), \quad (15)$$

where $b \in \mathcal{D}_n$ is determined by the relay selection criterion of (12).

C. Multi-Relay Selection

This subsection proposes a multi-relay selection scheme, where given a non-empty set \mathcal{D}_n , all relays within \mathcal{D}_n are employed for simultaneously transmitting x_s to D. Explicitly, this differs from the single-relay selection scheme, in which only a single relay is chosen from \mathcal{D}_n for forwarding the source signal. A weight vector denoted by $\mathbf{w} = [w_1, w_2, \dots, w_{|\mathcal{D}_n|}]^T$ is employed by all the relays of \mathcal{D}_n in transmitting x_s , where $|\mathcal{D}_n|$ is the cardinality of \mathcal{D}_n . For the sake of a fair comparison with single-relay selection, the total transmit power of all relays is constrained to P and thus the weight vector \mathbf{w} should have unit norm (i.e., $\|\mathbf{w}\| = 1$). Hence, given a non-empty decoding set \mathcal{D}_n and considering that all relays within \mathcal{D}_n simultaneously transmit x_s using a weight vector \mathbf{w} , the signal received at D is written as

$$y_d^{\text{multi}} = \sqrt{P}\mathbf{w}^T \mathbf{h}_d x_s + n_d, \quad (16)$$

where $\mathbf{h}_d = [h_{1d}, h_{2d}, \dots, h_{|\mathcal{D}_n|d}]^T$. Meanwhile, the signal received at E can be expressed as

$$y_e^{\text{multi}} = \sqrt{P}\mathbf{w}^T \mathbf{h}_e x_s + n_e, \quad (17)$$

where $\mathbf{h}_e = [h_{1e}, h_{2e}, \dots, h_{|\mathcal{D}_n|e}]^T$. From (16) and (17), the received signal-to-noise ratios (SNRs) at D and E are, respectively, given by

$$\text{SNR}_d^{\text{multi}} = \gamma |\mathbf{w}^T \mathbf{h}_d|^2, \quad (18)$$

and

$$\text{SNR}_e^{\text{multi}} = \gamma |\mathbf{w}^T \mathbf{h}_e|^2. \quad (19)$$

In this paper, the weight vector \mathbf{w} is optimized by maximizing the $\text{SNR}_d^{\text{multi}}$, yielding

$$\max_{\mathbf{w}} \text{SNR}_d^{\text{multi}}, \quad \text{s.t. } \|\mathbf{w}\| = 1, \quad (20)$$

where the constraint is used for normalization. Using the Cauchy-Schwarz inequality, we express the optimal weight vector \mathbf{w}_{opt} from (20) as

$$\mathbf{w}_{\text{opt}} = \frac{\mathbf{h}_d^*}{\|\mathbf{h}_d\|}, \quad (21)$$

where the optimal weight vector design only requires the CSI of the channel spanning from the relays to D (i.e., \mathbf{h}_d) without requiring the eavesdropper's CSI \mathbf{h}_e . Substituting \mathbf{w}_{opt} from (21) into (18) and (19), we obtain the channel capacities achieved at D and E as

$$C_d^{\text{multi}} = \frac{1}{2} \log_2(1 + \gamma \sum_{i \in \mathcal{D}_n} |h_{id}|^2), \quad (22)$$

and

$$C_e^{\text{multi}} = \frac{1}{2} \log_2(1 + \gamma \frac{|\mathbf{h}_d^H \mathbf{h}_e|^2}{\|\mathbf{h}_d\|^2}), \quad (23)$$

for $\mathcal{D} = \mathcal{D}_n$, where H denotes the Hermitian transpose.

III. SRT ANALYSIS OVER RAYLEIGH FADING CHANNELS

In this section, we present the SRT analysis of the classic direct transmission as well as of both single-relay and multi-relay selection schemes over Rayleigh fading channels. As discussed in [17], the wireless security and reliability are characterized using the intercept probability and outage probability experienced by the eavesdropper and destination, respectively. Let us first recall the definitions of outage probability and intercept probability.

Definition 1: Denoting the channel capacities achieved at the destination and eavesdropper by C_d and C_e , the outage probability and intercept probability are defined as [17], [20]

$$P_{\text{out}} = \Pr(C_d < R), \quad (24)$$

and

$$P_{\text{int}} = \Pr(C_e > R), \quad (25)$$

where R represents the data rate.

A. Direct Transmission

From (24), the outage probability of the direct transmission is obtained as

$$P_{\text{out}}^{\text{direct}} = \Pr(C_{sd} < R), \quad (26)$$

where C_{sd} is given by (3). Substituting C_{sd} from (3) into (26) yields

$$P_{\text{out}}^{\text{direct}} = \Pr(|h_{sd}|^2 < \Delta), \quad (27)$$

where $\Delta = (2^R - 1)/\gamma$. Noting that $|h_{sd}|^2$ is an exponentially distributed random variable with a mean of σ_{sd}^2 , we arrive at

$$P_{\text{out}}^{\text{direct}} = 1 - \exp(-\frac{\Delta}{\sigma_{sd}^2}). \quad (28)$$

Additionally, we obtain the intercept probability of the direct transmission from (4) and (25) as

$$P_{\text{int}}^{\text{direct}} = \Pr(C_{se} > R) = \exp(-\frac{\Delta}{\sigma_{se}^2}), \quad (29)$$

where σ_{se}^2 is the expected value of the random variable $|h_{se}|^2$.

B. Single-Relay Selection

This subsection presents the SRT analysis of the single-relay selection scheme. Using the law of total probability, the outage probability of the single-relay selection scheme is given by

$$P_{\text{out}}^{\text{single}} = \Pr(C_{bd} < R, \mathcal{D} = \emptyset) + \sum_{n=1}^{2^N-1} \Pr(C_{bd} < R, \mathcal{D} = \mathcal{D}_n), \quad (30)$$

where C_{bd} represents the capacity of the channel spanning from the “best” relay to D. In the case of $\mathcal{D} = \emptyset$, no relay is chosen to forward the source signal, leading to $C_{bd} = 0$. Substituting this result into (30) gives

$$P_{\text{out}}^{\text{single}} = \Pr(\mathcal{D} = \emptyset) + \sum_{n=1}^{2^N-1} \Pr(C_{bd} < R, \mathcal{D} = \mathcal{D}_n). \quad (31)$$

Using (8), (9) and (13), we can rewrite (31) as

$$P_{\text{out}}^{\text{single}} = \prod_{i=1}^N \Pr(|h_{si}|^2 < \Lambda) + \sum_{n=1}^{2^N-1} \prod_{i \in \mathcal{D}_n} \Pr(|h_{si}|^2 > \Lambda) \prod_{j \in \bar{\mathcal{D}}_n} \Pr(|h_{sj}|^2 < \Lambda) \times \Pr(\max_{i \in \mathcal{D}_n} |h_{id}|^2 < \Lambda), \quad (32)$$

where $\Lambda = (2^{2R} - 1)/\gamma$. Noting that $|h_{si}|^2$ and $|h_{id}|^2$ are independent exponentially distributed random variables with respective means of σ_{si}^2 and σ_{id}^2 , we obtain

$$\Pr(|h_{si}|^2 < \Lambda) = 1 - \exp(-\frac{\Lambda}{\sigma_{si}^2}), \quad (33)$$

and

$$\Pr(\max_{i \in \mathcal{D}_n} |h_{id}|^2 < \Lambda) = \prod_{i \in \mathcal{D}_n} \left[1 - \exp(-\frac{\Lambda}{\sigma_{id}^2}) \right]. \quad (34)$$

Moreover, the intercept probability of the single-relay selection scheme is obtained from (25) as

$$P_{\text{int}}^{\text{single}} = \Pr(C_{be} > R, \mathcal{D} = \emptyset) + \sum_{n=1}^{2^N-1} \Pr(C_{be} > R, \mathcal{D} = \mathcal{D}_n), \quad (35)$$

where C_{be} denotes the capacity of the channel spanning from the “best” relay to E. Given $\mathcal{D} = \emptyset$, we have $C_{be} = 0$, since no relay re-transmits the source signal. Hence, substituting this result into (35) and using (8), (9) and (15), we obtain

$$P_{\text{int}}^{\text{single}} = \sum_{n=1}^{2^N-1} \prod_{i \in \mathcal{D}_n} \Pr(|h_{si}|^2 > \Lambda) \prod_{j \in \bar{\mathcal{D}}_n} \Pr(|h_{sj}|^2 < \Lambda) \times \Pr(|h_{be}|^2 > \Lambda), \quad (36)$$

where the closed-form expressions of $\Pr(|h_{si}|^2 > \Lambda)$ and $\Pr(|h_{sj}|^2 < \Lambda)$ can be readily derived by using (33). Proceeding as in Appendix A, we obtain $\Pr(|h_{be}|^2 > \Lambda)$ as

$$\Pr(|h_{be}|^2 > \Lambda) = \sum_{i \in \mathcal{D}_n} \exp\left(-\frac{\Lambda}{\sigma_{ie}^2}\right) \times \left[1 + \sum_{m=1}^{2^{|\mathcal{D}_n|-1}-1} (-1)^{|C_n(m)|} \left(1 + \sum_{j \in C_n(m)} \frac{\sigma_{id}^2}{\sigma_{jd}^2}\right)^{-1} \right], \quad (37)$$

where $C_n(m)$ represents the m -th non-empty subset of " $\mathcal{D}_n - \{i\}$ " and ' $-$ ' represents the set difference.

C. Multi-Relay Selection

This subsection analyzes the SRT of multi-relay selection. Similarly to (31), the outage probability of multi-relay selection scheme is given by

$$P_{\text{out}}^{\text{multi}} = \Pr(\mathcal{D} = \emptyset) + \sum_{n=1}^{2^N-1} \Pr(C_d^{\text{multi}} < R, \mathcal{D} = \mathcal{D}_n). \quad (38)$$

Using (8), (9) and (22), we can rewrite (38) as

$$P_{\text{out}}^{\text{multi}} = \prod_{i=1}^N \Pr(|h_{si}|^2 < \Lambda) + \sum_{n=1}^{2^N-1} \prod_{i \in \mathcal{D}_n} \Pr(|h_{si}|^2 > \Lambda) \prod_{j \in \mathcal{D}_n} \Pr(|h_{sj}|^2 < \Lambda) \times \Pr\left(\sum_{i \in \mathcal{D}_n} |h_{id}|^2 < \Lambda\right), \quad (39)$$

where the closed-form expressions of $\Pr(|h_{si}|^2 < \Lambda)$, $\Pr(|h_{sj}|^2 > \Lambda)$ and $\Pr(|h_{sj}|^2 < \Lambda)$ can be easily determined as shown in (33). However, it is challenging to obtain the closed-form expression of $\Pr(\sum_{i \in \mathcal{D}_n} |h_{id}|^2 < \Lambda)$. For simplicity, we assume that the fading coefficients of all relay-destination channels $|h_{id}|^2$ are independent and identically distributed (i.i.d.) random variables with the same average channel gain denoted by $\sigma_d^2 = E(|h_{id}|^2)$. This assumption is widely used in the cooperative relaying literature [3]-[9] and it is valid in a statistical sense, when all relays are uniformly distributed geographically over a certain geographical area. Assuming that the random variables of $|h_{id}|^2$ for $i \in \mathcal{D}_n$ are i.i.d., we obtain

$$\Pr\left(\sum_{i \in \mathcal{D}_n} |h_{id}|^2 < \Lambda\right) = \Gamma\left(\frac{\Lambda}{\sigma_d^2}, |\mathcal{D}_n|\right), \quad (40)$$

where $\Gamma(x, k) = \int_0^x \frac{t^{k-1}}{\Gamma(k)} e^{-t} dt$ is known as the incomplete Gamma function. Let us now present the intercept probability analysis of the multi-relay selection scheme. Similarly to (36), the intercept probability of multi-relay selection can be obtained from (23) as

$$P_{\text{int}}^{\text{multi}} = \sum_{n=1}^{2^N-1} \prod_{i \in \mathcal{D}_n} \Pr(|h_{si}|^2 > \Lambda) \prod_{j \in \mathcal{D}_n} \Pr(|h_{sj}|^2 < \Lambda) \times \Pr\left(\frac{|\mathbf{h}_d^H \mathbf{h}_e|^2}{|\mathbf{h}_d|^2} > \Lambda\right), \quad (41)$$

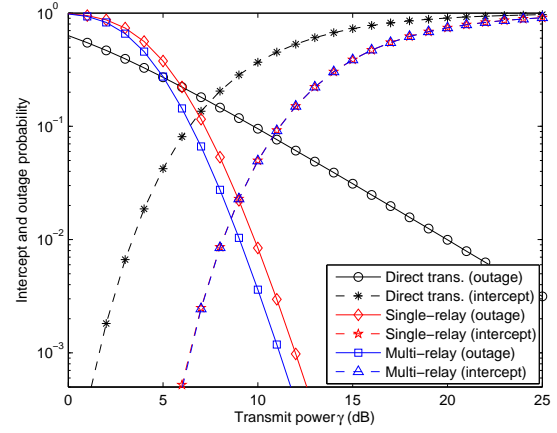


Fig. 3. Intercept probability and outage probability versus the transmit power γ of the direct transmission, the single-relay selection and the multi-relay selection schemes.

where the closed-form expressions of $\Pr(|h_{si}|^2 > \Lambda)$ and $\Pr(|h_{sj}|^2 < \Lambda)$ can be determined by using (33). However, it is challenging to obtain a closed-form solution for $\Pr(\frac{|\mathbf{h}_d^H \mathbf{h}_e|^2}{|\mathbf{h}_d|^2} > \Lambda)$. Although finding a general closed-form intercept probability expression is difficult for the multi-relay selection scheme, we can evaluate the numerical intercept probability through using computer simulations.

IV. NUMERICAL RESULTS AND DISCUSSIONS

In this section, we present the numerical SRT results of the direct transmission as well as of the single-relay and multi-relay selection schemes. Specifically, the intercept probability and outage probability of the three schemes are evaluated by using (28), (29), (32), (36), (39) and (41). In our numerical evaluation, the transmission link between any two nodes of Figs. 1 and 2 is modeled by the Rayleigh fading channel and the average channel gains are specified as $\sigma_{sd}^2 = \sigma_{si}^2 = \sigma_{id}^2 = 1$ and $\sigma_{se}^2 = \sigma_{ie}^2 = 0.1$. Additionally, an SNR of $\gamma = 10$ dB, a data rate of $R = 1$ bit/s/Hz, and $N = 6$ relays are assumed, unless otherwise stated.

Fig. 3 shows the intercept probability and outage probability versus the transmit power γ of the direct transmission as well as of the single-relay and multi-relay selection schemes. Notice that the numerical curves in Fig. 3 are obtained by plotting (28), (29), (32), (36), (39) and (41) as a function of the transmit power γ . It can be seen from Fig. 3 that as the transmit power increases, the outage probabilities of the direct transmission, the single-relay selection, and the multi-relay selection are reduced accordingly, whereas the corresponding intercept probabilities of the three schemes increase. This implies that a security and reliability trade-off between the intercept probability and outage probability exists for wireless transmissions in the presence of eavesdropping attacks. Fig. 3 also demonstrates that both the single-relay and multi-relay selection schemes outperform the classic direct transmission in terms of their intercept and outage probabilities. Moreover, the multi-relay selection strictly performs better than the single-relay selection in terms of the outage probability. Meanwhile,

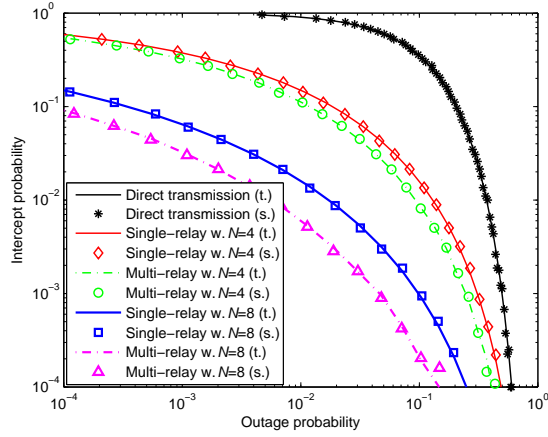


Fig. 4. Intercept probability versus outage probability of the direct transmission, the single-relay selection and the multi-relay selection schemes for different N , where ‘t.’ and ‘s.’ stand for theoretical and simulation results, respectively.

the intercept performance of the single-relay selection is almost identical to that of the multi-relay selection. Therefore, given a required intercept probability, the multi-relay selection scheme can achieve a better outage performance than the single-relay selection. Conversely, with a target outage requirement, the intercept probability of the multi-relay selection would be lower than that of the single-relay selection scheme.

In Fig. 4, the intercept probabilities of the direct transmission as well as the single-relay and multi-relay selection schemes are plotted as a function of the outage probability for $N = 4$ and $N = 8$ using (28), (29), (32), (36), (39) and (41). Meanwhile, simulation results of the intercept probability versus outage probability of the three schemes are also given in Fig. 4. It is observed from Fig. 4 that the SRTs of the single-relay and multi-relay selection schemes are consistently better than that of the direct transmission for both $N = 4$ and $N = 8$. Moreover, as the number of relays increases from $N = 4$ to $N = 8$, the SRTs of both single-relay and multi-relay selection improve significantly, demonstrating the security and reliability benefits of using cooperative relays. In other words, the security and reliability of wireless transmissions can be concurrently improved by increasing the number of relays. Also, Fig. 4 shows that for both $N = 4$ and $N = 8$, the multi-relay selection outperforms the single-relay selection in terms of their SRT performance. It is worth mentioning that in the proposed multi-relay selection scheme, multiple selected relays should simultaneously forward the source signal to the destination, which, however, requires the complex symbol-level synchronization among different relays to avoid inter-symbol interference. By contrast, the single-relay selection does not need such complex synchronization process. Therefore, the SRT advantage of the multi-relay selection over the single-relay selection is achieved at the cost of additional implementation complexity due to the symbol-level synchronization among the spatially distributed relays. Additionally, the theoretical and simulation results of Fig. 4 match well with each other, confirming the correctness of the SRT analysis.

V. CONCLUSIONS

In this paper, we studied the relay selection of a cooperative wireless network in the presence of an eavesdropper and proposed the multi-relay selection scheme for protecting wireless transmissions against eavesdropping. We used the classic direct transmission and single-relay selection as our benchmarks. We carried out the SRT analysis of the direct transmission as well as of both the single-relay and multi-relay selection schemes over Rayleigh fading channels. We showed that the single-relay and multi-relay selection schemes perform consistently better than the direct transmission in terms of their SRT performance. Moreover, the SRT of the multi-relay selection is better than that of single-relay selection. Finally, upon increasing the number of relays, the SRTs of both the single-relay and multi-relay selection schemes improve significantly, showing the advantage of exploiting cooperative relays for enhancing the wireless security and reliability.

VI. DERIVATION OF (37)

Given $\mathcal{D} = \mathcal{D}_n$, any relay within \mathcal{D}_n may be chosen as the “best” relay for forwarding the source signal to D. Thus, using the law of total probability, we have

$$\begin{aligned} \Pr(|h_{be}|^2 > \Lambda) &= \sum_{i \in \mathcal{D}_n} \Pr(|h_{ie}|^2 > \Lambda, b = i) \\ &= \sum_{i \in \mathcal{D}_n} \Pr(|h_{ie}|^2 > \Lambda, |h_{id}|^2 > \max_{j \in \mathcal{D}_n - \{i\}} |h_{jd}|^2) \quad (\text{B.1}) \\ &= \sum_{i \in \mathcal{D}_n} \Pr(|h_{ie}|^2 > \Lambda) \Pr(\max_{j \in \mathcal{D}_n - \{i\}} |h_{jd}|^2 < |h_{id}|^2), \end{aligned}$$

where the second equality is obtained by using (12) and ‘-’ denotes the set difference. Noting that $|h_{ie}|^2$ is an exponentially distributed random variable with a mean of σ_{ie}^2 , we arrive at

$$\Pr(|h_{ie}|^2 > \Lambda) = \exp(-\frac{\Lambda}{\sigma_{ie}^2}). \quad (\text{B.2})$$

Letting $|h_{jd}|^2 = x_j$ and $|h_{id}|^2 = y$, we have

$$\begin{aligned} &\Pr(\max_{j \in \mathcal{D}_n - \{i\}} |h_{jd}|^2 < |h_{id}|^2) \\ &= \int_0^\infty \frac{1}{\sigma_{id}^2} \exp(-\frac{y}{\sigma_{id}^2}) \prod_{j \in \mathcal{D}_n - \{i\}} [1 - \exp(-\frac{y}{\sigma_{jd}^2})] dy, \quad (\text{B.3}) \end{aligned}$$

wherein $\prod_{j \in \mathcal{D}_n - \{i\}} [1 - \exp(-\frac{y}{\sigma_{jd}^2})]$ is expanded by

$$\begin{aligned} &\prod_{j \in \mathcal{D}_n - \{i\}} [1 - \exp(-\frac{y}{\sigma_{jd}^2})] \\ &= 1 + \sum_{m=1}^{2^{|\mathcal{D}_n|} - 1} (-1)^{|C_n(m)|} \exp(-\sum_{j \in C_n(m)} \frac{y}{\sigma_{jd}^2}), \quad (\text{B.4}) \end{aligned}$$

where $C_n(m)$ represents the m -th non-empty subset of “ $\mathcal{D}_n - \{i\}$ ” and $|C_n(m)|$ is the cardinality of the set $C_n(m)$. Combining (B.3) and (B.4), we obtain

$$\begin{aligned} &\Pr(\max_{j \in \mathcal{D}_n - \{i\}} |h_{jd}|^2 < |h_{id}|^2) \\ &= 1 + \sum_{m=1}^{2^{|\mathcal{D}_n|} - 1} (-1)^{|C_n(m)|} (1 + \sum_{j \in C_n(m)} \frac{\sigma_{id}^2}{\sigma_{jd}^2})^{-1}. \quad (\text{B.5}) \end{aligned}$$

Substituting (B.2) and (B.5) into (B.1) gives (37).

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